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1. Your reference	MJB06427GB	
2. Patent applic *(The Patent Off...*	9912724.3	1 JUN 1999
3. Full name, address and postcode of the or of each applicant *(underline all surnames)*	Cambridge Positioning Systems Ltd 62-64 Hills Road Cambridge CB2 1LA	
Patents ADP number *(if you know it)*	7157628002	
If the applicant is a corporate body, give the country/state of its incorporation	United Kingdom	
4. Title of the invention	Radio Positioning System	
5. Name of your agent *(if you have one)*	GILL JENNINGS & EVERY	
"Address for service" in the United Kingdom to which all correspondence should be sent *(including the postcode)*	Broadgate House 7 Eldon Street London EC2M 7LH	
Patents ADP number *(if you know it)*	745002	

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Claim*(s)*	
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Request for preliminary examination and search *(Patents Form 9/77)*	
Request for substantive examination *(Patents Form 10/77)*	
Any other documents *(please specify)*	

11. For the Applicant
Gill Jennings & Every

I/We request the grant of a patent on the basis of this application.

Signature

Date 1 June 1999

12. Name and daytime telephone number of person to contact in the United Kingdom

BRUNNER, Michael ~~John~~
0171 377 1377

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RADIO POSITIONING SYSTEM

The present invention relates to a radio positioning system.

EP-A-0 303 371, the contents of which are hereby incorporated by reference, describes a radio navigation and tracking system which makes use of independent radio transmitters set up for other purposes. The signals from each transmitter, taken individually, are received by two receiving stations, one at a fixed and known location, and the other mounted on the mobile object whose position is to be determined. A representation of the signals received at one receiving station is sent via a link to a processor at the other receiving station, where the received signals are compared to find their phase differences or time delays. Three such measurements, made on three widely spaced independent transmitters, are sufficient to determine the position of the mobile receiver in two dimensions, i.e. its position on the ground. The phase or time offset between the master oscillators in the two receivers is also determined.

"CURSOR", as the system described in EP-A-0 303 371 is known, is a radio positioning system which can use the signals radiated by existing non-synchronised radio transmitters to locate the position of a portable receiver. Unlike some other systems which use the temporal coherence properties of networks of purpose-built synchronised transmitters, CURSOR makes use of the spatial coherence of the signals transmitted by single transmitters. In a further development (see EP-A-0 880 712 & WO-A-99/21028), the technology has been applied to find the position of a mobile phone handset in a GSM or other digital telephone system, and these are examples of an 'Enhanced Observed Time Difference' (EOTD) method using the down-link signals radiated by the network of Base Transceiver Stations (BTS) of the telephone system.

In the digital mobile telephone application described in EP-A-0 880 712, the signals from each BTS within range of the handset are received both by the handset itself and by a fixed nearby receiver, the Location Measurement Unit (LMU), whose position is accurately known. Representations of the received signals are passed to a Mobile Location Centre (MLC) where they are compared in order to find the time difference between them. In Figure 1 we show the geometry of a standard two-dimensional

system. The origin of Cartesian co-ordinates x and y is centred on the LMU positioned at O. The orientation of the axes is immaterial, but may conveniently be set so that the y axis lies along the north-south local map grid. The handset, R, is at vector position **r** with respect to the LMU position O. A BTS, A, is shown at vector position **a**.

Consider first the signals from BTS A. The time difference, Δt_a, measured between the signals received at O and R is given by

$$\Delta t_a = (|\mathbf{r} - \mathbf{a}| - |\mathbf{a}|)/\upsilon + \varepsilon ,$$

where υ is the speed of the radio waves, and ε is the clock time offset between the clocks in the receivers at O and R. The value of ε represents the synchronisation error between the measurements made by the two receivers. Similarly, we may write for two other BTSs (B and C) at vector positions **b** and **c** (not shown):

$$\Delta t_b = (|\mathbf{r} - \mathbf{b}| - |\mathbf{b}|)/\upsilon + \varepsilon ,$$

$$\Delta t_c = (|\mathbf{r} - \mathbf{c}| - |\mathbf{c}|)/\upsilon + \varepsilon . \qquad \textbf{(1)}$$

The values of Δt_a , Δt_b , Δt_c, are measured by the methods disclosed in EP-A-0 880 712 and the values of **a**, **b**, **c**, and υ are known. Hence the equations (1) can be solved to find the position of the handset, **r.**

In WO-A-99/21028 we describe how these same time offsets can be measured using locally-created *templates* in a GSM telephone system as follows. Suppose that the handset has recorded a short burst of the GSM signals from BTS A. Contained within that recording is the framing structure, synchronisation bursts and other 'given' data (or predetermined values) which are a constant feature of those transmissions. The processor within the handset can create a matching template, based on the known structure of the network signals. Received signals can then be matched by the locally-generated template. When the template finds a match, the correlation peak at the position of best match corresponds to the time offset between the received signals and the local clock inside the handset. This time offset, Δt_{a1} is given by

$$\Delta t_{a1} = (|\mathbf{r} - \mathbf{a}|)/\upsilon + \alpha_a + \varepsilon_1 \,,$$

where α_a is the time offset of the BTS transmissions and ε_1 is the time offset of the handset's internal clock, both relative to an imaginary universal 'absolute' clock. The signals from BTSs B and C may also be measured in the same way, giving

$$\Delta t_{b1} = (|\mathbf{r} - \mathbf{b}|)/\upsilon + \alpha_b + \varepsilon_1,$$

and

$$\Delta t_{c1} = (|\mathbf{r} - \mathbf{c}|)/\upsilon + \alpha_c + \varepsilon_1 \,. \qquad \textbf{(2)}$$

The same measurements can also be made by the LMU, giving

$$\Delta t_{a2} = (|\mathbf{a}|)/\upsilon + \alpha_a + \varepsilon_2 \,,$$

$$\Delta t_{b2} = (|\mathbf{b}|)/\upsilon + \alpha_b + \varepsilon_2 \,,$$

and

$$\Delta t_{c2} = (|\mathbf{c}|)/\upsilon + \alpha_c + \varepsilon_2 \,, \qquad \textbf{(3)}$$

where ε_2 is the time offset of the LMU's internal clock relative to the imaginary universal absolute clock. Subtracting equations 3 from 2 gives us

$$\Delta t_a = \Delta t_{a1} - \Delta t_{a2} = (|\mathbf{r} - \mathbf{a}| - |\mathbf{a}|)/\upsilon + \varepsilon \,,$$

$$\Delta t_b = \Delta t_{b1} - \Delta t_{b2} = (|\mathbf{r} - \mathbf{b}| - |\mathbf{b}|)/\upsilon + \varepsilon \,,$$

and

$$\Delta t_c = \Delta t_{c1} - \Delta t_{c2} = (|\mathbf{r} - \mathbf{c}| - |\mathbf{c}|)/\upsilon + \varepsilon \,, \qquad \textbf{(4)}$$

where $\varepsilon = \varepsilon_1 - \varepsilon_2$. It will be noted that equations 4 are just like equations 1, and can be solved in the same way to find the position of the handset, **r**.

It will be apparent that the CURSOR method, in common with all other EOTD methods, requires a network of LMUs to be set up within the coverage area of the telephone system. These units act as reference points at which the unsynchronised signals radiated by the BTSs are measured for comparison with the same signals received by a handset. Each position measurement requires a match to be made between the signals received by the handset from a number of nearby BTSs, and signals received by an LMU from the same set of BTSs. In practice, it is often difficult to find a match using just one LMU, especially if the LMU network is sparse. It is therefore necessary to combine the measurements from two or more LMUs. However, each new LMU brought into the calculation adds a further unknown clock time offset (ε_2, ε_3 etc.), each of which therefore requires an additional BTS to be measured to provide the extra equations needed to solve for all the unknown quantities. A minimum set of measurements for positioning in two dimensions requires at least three geometrically-dispersed BTSs in the set if one LMU is involved. Adding a second LMU increases the minimum number of BTSs required to four, and so on.

One solution to this problem is presented in WO-A-99/21028 where it is shown how the LMU network can be synchronised. Suppose that an adjacent pair of LMUs, L_1 and L_2, can see a common BTS. The positions of the LMUs and the BTS are all known, so a single measurement of the BTS signals by each LMU is sufficient to determine the clock time offset between the LMUs. For example, suppose that the distance from L_1 to the BTS is s_1, and the distance from L_2 to the BTS is s_2. L_1 measures time offset Δt_1 and L_2 measures Δt_2, given by

$$\Delta t_1 = s_1/\upsilon + \alpha + \varepsilon_2 ,$$

$$\Delta t_2 = s_2/\upsilon + \alpha + \varepsilon_3 ,$$

where α is the time offset of the BTS transmissions, and ε_2 and ε_3 are the time offsets of the LMU internal clocks. Subtracting the second equation from the first yields

$$\varepsilon_2 - \varepsilon_3 = \Delta t_1 - \Delta t_2 + s_1/\upsilon - s_2/\upsilon ,$$

which is the relative time offset of L_1 with respect to L_2. This process may be repeated for a second pair of LMUs, say L_2 and L_3, and another BTS whose signals can be received by both of these second pair of LMUs. In this way a synchronisation map may be calculated, which provides the clock offsets of all the LMU internal clocks relative to one of them adopted as the master 'LMU network clock time'. Having established the LMU synchronisation map in this fashion, a CURSOR position measurement can include any number of LMUs without the penalty of adding an extra unknown quantity for every LMU.

The present invention teaches how the same advantages of a synchronised LMU network may be obtained by setting up one or more 'virtual LMUs' in the network which act as interface nodes for the real LMUs.

According to a first aspect of the invention, there is provided a method of generating a list of the timing or phase offsets of a plurality of transmission sources relative to a common timing reference, the method comprising

(a) acquiring data from one or more receivers, the positions of which are known or determined, the data from a receiver comprising timing or phase offsets of signals received from the transmission sources relative to a timing reference source or to each other; and

(b) combining the acquired data and producing a list of the offsets, relative to the common timing reference, of a number of the transmission sources.

In practice, particularly when the transmission sources are transmitters in a digital mobile telephone network, the offsets from the list are used in place of offsets obtained directly from the receiver or receivers.

In a method using techniques similar to or as described in EP-A-0 880 712, in place of timing or phase offsets, data representative of the received signals from which the timing or phase offsets of signals received from the transmission sources relative to the timing reference source may be used.

Therefore an alternative first aspect of the invention comprises a method of generating a list of the timing or phase offsets of a plurality of transmission sources relative to a common timing reference, the method comprising

(c) acquiring data from one or more receivers, the positions of which are known or determined, the data from a receiver being representative of the received signals from which the timing or phase offsets of signals received from the transmission sources relative to a timing reference source or to each other may be determined; and

(d) combining the acquired data and producing a list of the offsets, relative to the common timing reference, of a number of the transmission sources.

The invention also includes apparatus (a 'virtual LMU') for carrying out either or both of these methods. The apparatus may include a computer located at any one of a number of places connected to the network and programmed to carry out the required process.

A virtual LMU is a computer process which may run on any computer platform connected to the network. It is assumed that the network of BTSs is *unsynchronised* in that the relative phases (the relative transmission delays) of the BTS signals bear no constant or known relationship to each other, but that nevertheless the BTS oscillators are quite *stable*, so that their relative phases change only slowly with time. In these circumstances, it is possible to predict the current relative phases from sufficiently-recent historical data. The real LMUs in the network make measurements of all the BTSs they can detect in a cyclic fashion, repeating the cycle every few seconds. They maintain these measurements in a stack, replacing the oldest measurements with the most recent. A linear or low-order polynomial fit to the measurements therefore provides a predictor for extrapolation into the near future, or for interpolation in the recent past. Let us suppose that the phases are sufficiently stable that reliable

predictions can be made over a period of, say, ten minutes. Then every ten minutes, the virtual LMU (VLMU) contacts each real LMU and receives its predictors for the BTSs in its measurement set. It is likely that many of the BTSs will have been measured by more than one LMU, so the VLMU analyses the complete data set from all the real LMUs to determine the best values of the LMU clock time offsets and the BTS relative phases using well-known methods.

By way of example, one such method is now described. Consider a network of N LMUs and M BTSs. Let the position of the nth LMU be represented by the vector $\mathbf{L}_n$ and let the position of the mth BTS be represented by the vector $\mathbf{B}_m$, both measured with respect to the same origin. Signals radiated by BTS m will be received by LMU n after a time lag, Δt_{nm}, where

$$\Delta t_{nm} = |\mathbf{L}_n - \mathbf{B}_m|/\upsilon + \varepsilon_n + \alpha_m \pm \sigma_{nm} ,$$

ε_n is the clock offset of LMU n, and α_m is the clock offset of BTS m, both with respect to an imaginary universal 'absolute' clock, and σ_{nm} is an estimate of the error in the measurement of Δt_{nm}. Over the entire network of N LMUs, all of the M BTSs are visible. Each individual LMU, however, will only see a few of them, but as long as there is significant overlap of visibility, it is possible to take the set of all Δt values and solve for values of ε_n and α_m. Hence the VLMU can calculate timings for any BTS as if the network of LMUs were synchronised.

To illustrate this, a simplified problem is shown and solved below using $N = 2$ and $M = 4$. We choose $\varepsilon_1 = 0$ for simplicity. We are allowed to do this as the 'absolute' clock time is completely arbitrary and may, for example, be measured by the internal clock of LMU number one. The equations can be written in matrix form

$$\begin{pmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 1 \end{pmatrix} \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \alpha_3 \\ \alpha_4 \\ \varepsilon_2 \end{pmatrix} = \begin{pmatrix} \Delta t_{11} - \frac{|\mathbf{L}_1 - \mathbf{B}_1|}{\upsilon} \\ \Delta t_{12} - \frac{|\mathbf{L}_1 - \mathbf{B}_2|}{\upsilon} \\ \Delta t_{13} - \frac{|\mathbf{L}_1 - \mathbf{B}_3|}{\upsilon} \\ \Delta t_{21} - \frac{|\mathbf{L}_2 - \mathbf{B}_1|}{\upsilon} \\ \Delta t_{22} - \frac{|\mathbf{L}_2 - \mathbf{B}_2|}{\upsilon} \\ \Delta t_{24} - \frac{|\mathbf{L}_2 - \mathbf{B}_4|}{\upsilon} \end{pmatrix} + \mathbf{V}$$

or equivalently as $\mathbf{A.x} = \mathbf{b} + \mathbf{V}$, where $\mathbf{V}$ is an unknown vector of the actual errors on each measurement. Let the matrix $\mathbf{W}$ be defined by

$$\mathbf{W} = \begin{pmatrix} \frac{1}{\sigma_{11}^2} & 0 & 0 & 0 & 0 & 0 \\ 0 & \frac{1}{\sigma_{12}^2} & 0 & 0 & 0 & 0 \\ 0 & 0 & \frac{1}{\sigma_{13}^2} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\sigma_{21}^2} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{\sigma_{22}^2} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{\sigma_{24}^2} \end{pmatrix}.$$

The standard technique known as 'least squares' postulates that the estimate for $\mathbf{x}$ which minimises $\mathbf{V}$ is given by

$$\mathbf{x} = (\mathbf{A}^{\mathbf{T}}\mathbf{WA})^{-1}\,\mathbf{A}^{\mathbf{T}}\mathbf{Wb}\,.$$

This particular example can be solved explicitly. For simplicity, let us assume that all the values of σ_{nm} are the same, and equal to σ. This gives the result

$$\alpha_1 = (\,3D_{11} + D_{12} + D_{21} - D_{22}\,)/4 \qquad \pm 0.87\sigma,$$
$$\alpha_2 = (\,3D_{12} + D_{11} + D_{22} - D_{21}\,)/4 \qquad \pm 0.87\sigma,$$
$$\alpha_3 = D_{13} \qquad \pm 1.00\sigma,$$
$$\alpha_4 = (\,2D_{24} + D_{11} + D_{12} - D_{21} - D_{22}\,)/2 \qquad \pm 1.41\sigma,$$

$$\varepsilon_2 = (D_{21} + D_{22} - D_{11} - D_{12})/2 \qquad \pm 1.00\sigma,$$

where $D_{nm} = \Delta t_{nm} - \dfrac{|\mathbf{L}_n - \mathbf{B}_m|}{\upsilon}$.

Note that even in this simple case, when a BTS is seen by both LMUs, the errors in the calculated offsets are less than those in each of the measurements themselves. This is an important advantage of the virtual LMU method.

The LMUs may also contain other means of synchronisation. For example, each real LMU could be connected to a GPS or other timing reference receiver which serves to provide the common timing reference. In this case, the LMU network may be considered as synchronised already to this common timing reference (say GPS standard time), and then the VLMU need not solve for the individual values of ε as these are already known.

The VLMU mode of operation described above may be called the 'pull mode' as it requires the VLMU to instigate data transfer to itself from every real LMU. It is also possible to have each real LMU continuously check the difference between its own prediction of every BTS phase using the last predictor sent to the VLMU and the actual measured phase. When this difference exceeds a given value, it can send its new predictor set to the VLMU. This mode of operation may be called the 'push mode'. The particular mode appropriate for a real system depends, amongst other things, on the stability of the BTS network.

A second aspect of the present invention shows how the CURSOR method (or other EOTD method) can be applied without the need of a network of real LMUs.

According to the second aspect of the invention there is provided a method of determining the position or change in position of a receiver or receivers in a network of transmission sources, the method comprising

(a) at a first time, measuring the relative time or phase offsets with respect to each other or with respect to a timing reference source of the signals received by the receiver from a plurality of the transmission sources;

(b) at a selected second later time, measuring the relative time or phase offsets with respect to each other or with respect to a timing reference source of the signals received by the same or another of the receivers from a plurality of the transmission sources;

(c) calculating the relationship between first and second curves representing the loci of possible positions of the receiver or receivers at the first and second times respectively; and

(d) determining the position or change in position of the receiver or receivers at the first or second times from the positions of the intersections of the curves.

In the method defined above, the receivers may be the same receiver.

The second aspect of the invention also includes a method of determining the position or change in position of one of a plurality of receivers, the positions of all of which are unknown, in a network of transmission sources, the method comprising

(e) at a first time, measuring the relative time or phase offsets with respect to each other or with respect to a timing reference source of the signals received by the receiver from a plurality of the transmission sources;

(f) at a selected second time, measuring the relative time or phase offsets with respect to each other or with respect to a timing reference source of the signals received by the same or another of the receivers from a plurality of the transmission sources;

(g) calculating the relationship between first and second curves representing the loci of possible positions of the receiver or receivers at the first and second times respectively; and

(h) determining the position or change in position of the receiver or receivers at the first or second times from the positions of the intersections of the curves.

In the method defined above, the first and second times may be the same time.

The invention also includes apparatus for carrying out either or both of these methods, which apparatus may include receivers suitably programmed.

To illustrate one example, in which the transmitters and receivers are part of a digital mobile telephone network, let us suppose that the handset is at vector position $\mathbf{r}(t_1)$ at time t_1. Equations (2) are then

$$\Delta t_{a1}(t_1) = (|\mathbf{r}(t_1) - \mathbf{a}|)/\upsilon + \alpha_a(t_1) + \varepsilon_1(t_1)\,,$$

$$\Delta t_{b1}(t_1) = (|\mathbf{r}(t_1) - \mathbf{b}|)/\upsilon + \alpha_b(t_1) + \varepsilon_1(t_1),$$

$$\Delta t_{c1}(t_1) = (|\mathbf{r}(t_1) - \mathbf{c}|)/\upsilon + \alpha_c(t_1) + \varepsilon_1(t_1), \qquad \mathbf{(5)}$$

where $\varepsilon_a(t_1)$ is the time offset of the BTS transmissions from A, $\varepsilon_b(t_1)$ the offset from B, $\varepsilon_c(t_1)$ the offset from C, and $\varepsilon_1(t_1)$ is the time offset of the handset's internal clock, all measured at time t_1 relative to an imaginary universal 'absolute' clock. Now let the handset be at a different vector position $\mathbf{r}(t_2)$ at a later time t_2. Equations (2) are then

$$\Delta t_{a1}(t_2) = (|\mathbf{r}(t_2) - \mathbf{a}|)/\upsilon + \alpha_a(t_2) + \varepsilon_1(t_2)\,,$$

$$\Delta t_{b1}(t_2) = (|\mathbf{r}(t_2) - \mathbf{b}|)/\upsilon + \alpha_b(t_2) + \varepsilon_1(t_2),$$

$$\Delta t_{c1}(t_2) = (|\mathbf{r}(t_2) - \mathbf{c}|)/\upsilon + \alpha_c(t_2) + \varepsilon_1(t_2). \qquad \mathbf{(6)}$$

Subtracting equations (6) from equations (5) gives

$$\Delta t_{a1}(t_1) - \Delta t_{a1}(t_2) = (|\mathbf{r}(t_1) - \mathbf{a}| - |\mathbf{r}(t_2) - \mathbf{a}|)/\upsilon + (\alpha_a(t_1) - \alpha_a(t_2)) + (\varepsilon_1(t_1) - \varepsilon_1(t_2))\,,$$

$$\Delta t_{b1}(t_1) - \Delta t_{b1}(t_2) = (|\mathbf{r}(t_1) - \mathbf{b}| - |\mathbf{r}(t_2) - \mathbf{b}|)/\upsilon + (\alpha_b(t_1) - \alpha_b(t_2)) + (\varepsilon_1(t_1) - \varepsilon_1(t_2)),$$

$$\Delta t_{c1}(t_1) - \Delta t_{c1}(t_2) = (|\mathbf{r}(t_1) - \mathbf{c}| - |\mathbf{r}(t_2) - \mathbf{c}|)/\upsilon + (\alpha_c(t_1) - \alpha_c(t_2)) + (\varepsilon_1(t_1) - \varepsilon_1(t_2)). \qquad \mathbf{(7)}$$

As has been noted above, the BTS transmissions in a GSM or other digital network are not usually synchronised. However, they are often derived from a common reference timing source. Where this is the case, the signals therefore keep a constant phase offset with respect to each other, so $\varepsilon_a(t_1) = \varepsilon_a(t_2)$, $\varepsilon_b(t_1) = \varepsilon_b(t_2)$, and $\varepsilon_c(t_1) = \varepsilon_c(t_2)$. (Even where this is not the case, the BTS signals are often sufficiently stable to allow an estimate to be made of these differences in a VLMU or other network element.) Writing $\Delta t_a = \Delta t_{a1}(t_1) - \Delta t_{a1}(t_2)$, $\Delta t_b = \Delta t_{b1}(t_1) - \Delta t_{b1}(t_2)$, $\Delta t_c = \Delta t_{c1}(t_1) - \Delta t_{c1}(t_2)$, and $\varepsilon = \varepsilon_1(t_1) - \varepsilon_1(t_2)$, we get

$$\Delta t_a = (|\mathbf{r}(t_1) - \mathbf{a}| - |\mathbf{r}(t_2) - \mathbf{a}|)/\upsilon + \varepsilon,$$

$$\Delta t_b = (|\mathbf{r}(t_1) - \mathbf{b}| - |\mathbf{r}(t_2) - \mathbf{b}|)/\upsilon + \varepsilon,$$

$$\Delta t_c = (|\mathbf{r}(t_1) - \mathbf{c}| - |\mathbf{r}(t_2) - \mathbf{c}|)/\upsilon + \varepsilon. \qquad \mathbf{(8)}$$

Equations (8) can be understood graphically by reference to Figure 2. The diagram represents the plane of the Earth's surface (assumed to be flat) near to BTS units A and B. In the first of the equations, the term $|\mathbf{r}(t_1) - \mathbf{a}|$ represents the distance of the handset from A at time t_1, and the term $|\mathbf{r}(t_2) - \mathbf{a}|$ represents its distance at time t_2. The first of equations (8) can be rewritten as

$$|\mathbf{r}(t_1) - \mathbf{a}| - |\mathbf{r}(t_2) - \mathbf{a}| = \upsilon\Delta t_a - \upsilon\varepsilon,$$

which therefore represents the loci of two concentric circles centred on A whose radii differ by $\upsilon\Delta t_a - \upsilon\varepsilon$. These are marked 1 and 2 respectively in Figure 2. The above equation does not define the radius of either circle, but only the difference between them. By itself, this equation therefore does nothing to locate either of the points $\mathbf{r}(t_1)$ or $\mathbf{r}(t_2)$. Also marked in Figure 2 are a second pair of concentric circles, 3 and 4, representing the second of the equations (8) and centred on B. Again, their radii are unconfined by the equation, but the difference between their radii must be $\upsilon\Delta t_b - \upsilon\varepsilon$. Point $\mathbf{r}(t_1)$ must lie at one of the intersections of circles 1 and 3, and point $\mathbf{r}(t_2)$ must lie at one of the intersections of circles 2 and 4. Let us suppose that the value of ε is zero, i.e. that the handset's internal clock has kept perfect time between the

measurements. Then if we know the position of point $\mathbf{r}(t_1)$, say P in Figure 2, we can deduce that point $\mathbf{r}(t_2)$ must be at Q, because the four circles are now fixed in space, and hence we have measured the position of the handset at the later time. In practice, we can't assume that ε is zero, so we must use all three of equations (8) to find Q given P.

It will be noted there is also a second point of intersection, Q', of the circles 2 and 4, and hence an ambiguity in the determination of $\mathbf{r}(t_2)$. If this ambiguity cannot be resolved by other means (for example, by knowing that the handset is being used by a pedestrian who could not have moved from P to Q' in time $t_2 - t_1$) then four measurements involving four BTSs must be used.

One of the advantages of the second aspect of the present invention is that if a single handset makes measurements of the signals from a minimum of three geographically separate BTSs at two different times, then it is possible to determine the *change* in the position of the handset between these two times (without reference to a known starting point), provided that at least three of the BTSs are common to the two sets of measurements. If the position of the handset has been determined at some point previously, use of this technique may enable applications requiring autonomous navigation within the handset, i.e. navigation without further reference to the CURSOR or any other EOTD system.

The above discussion shows how the position of a handset at a later time can be obtained from three CURSOR-like measurements on three geographically-dispersed BTSs made both at the later time and at an earlier time provided (a) that the position of the handset is known at the earlier time, and (b) that there is no relative drift between the signals radiated by the BTSs in the interval (or that such drift is known). The accuracy of the position determination depends both on the precision with which the first position is known and on the distance moved between the measurements. Equations (8) actually contain five unknown quantities: the x and y co-ordinates of each of the two points P and Q, and the unknown handset clock drift ε. CURSOR-like measurements on each of five geographically-dispersed BTSs at both a first and a second position are therefore sufficient to determine both P and Q uniquely if the

handset has moved appreciably between the two sets of measurements. Here, then, is an EOTD method of finding the position of a moving handset in an unsynchronised digital mobile phone network without the need of any LMUs at all. It may be especially useful for tracking the handset in a network which does not already have a location system.

A further advantage of the second aspect of the present invention is to use the known position of one handset to find the unknown position of a second handset. Suppose that each handset makes a measurement at about the same time using three geographically-dispersed BTSs. Equations 5 for the first handset, H_1, are then

$$\Delta t_{a1}(t_1) = (|\mathbf{r}_1(t_1) - \mathbf{a}|)/\upsilon + \alpha_a(t_1) + \varepsilon_1(t_1)\,,$$

$$\Delta t_{b1}(t_1) = (|\mathbf{r}_1(t_1) - \mathbf{b}|)/\upsilon + \alpha_b(t_1) + \varepsilon_1(t_1),$$

$$\Delta t_{c1}(t_1) = (|\mathbf{r}_1(t_1) - \mathbf{c}|)/\upsilon + \alpha_c(t_1) + \varepsilon_1(t_1), \qquad \textbf{(9)}$$

where $\mathbf{r}_1(t_1)$ is the (known) position of H_1 and the measurements are made at time t_1. The same equations for the second handset, H_2, are

$$\Delta t_{a1}(t_2) = (|\mathbf{r}_2(t_2) - \mathbf{a}|)/\upsilon + \alpha_a(t_2) + \varepsilon_2(t_2)\,,$$

$$\Delta t_{b1}(t_2) = (|\mathbf{r}_2(t_2) - \mathbf{b}|)/\upsilon + \alpha_b(t_2) + \varepsilon_2(t_2),$$

$$\Delta t_{c1}(t_2) = (|\mathbf{r}_2(t_2) - \mathbf{c}|)/\upsilon + \alpha_c(t_2) + \varepsilon_2(t_2), \qquad \textbf{(10)}$$

where $\mathbf{r}_2(t_2)$ is the (unknown) position of H_2 and the measurements are made at time t_2. Subtracting equations (10) from equations (9), noting that $\alpha_a(t_1) = \alpha_a(t_2)$, $\alpha_b(t_1) = \alpha_b(t_2)$, and $\alpha_c(t_1) = \alpha_c(t_2)$, and writing $\Delta t_a = \Delta t_{a1}(t_1) - \Delta t_{a1}(t_2)$, $\Delta t_b = \Delta t_{b1}(t_1) - \Delta t_{b1}(t_2)$, $\Delta t_c = \Delta t_{c1}(t_1) - \Delta t_{c1}(t_2)$, and $\varepsilon = \varepsilon_1(t_1) - \varepsilon_2(t_2)$, we get

$$\Delta t_a = (|\mathbf{r}_1(t_1) - \mathbf{a}| - |\mathbf{r}_2(t_2) - \mathbf{a}|)/\upsilon + \varepsilon,$$

$$\Delta t_b = (|\mathbf{r}_1(t_1) - \mathbf{b}| - |\mathbf{r}_2(t_2) - \mathbf{b}|)/\upsilon + \varepsilon,$$

$$\Delta t_c = (|\mathbf{r}_1(t_1) - \mathbf{c}| - |\mathbf{r}_2(t_2) - \mathbf{c}|)/\upsilon + \varepsilon, \qquad \mathbf{(11)}$$

which are identical to equations (8) in form. Hence, given $\mathbf{r}_1(t_1)$, the position of H_1 at time t_1, we can calculate $\mathbf{r}_2(t_2)$ which is the position of H_2 at time t_2. (Again, measurements on four BTSs are needed to resolve the ambiguity in $\mathbf{r}_2(t_2)$ if this cannot be resolved by other means.) In this case, t_1 may be equal to t_2.

This same idea can be extended to many handsets. In equations (11), the vector $\mathbf{r}_1(t_1)$ refers to a first handset whose position is known, and the vector $\mathbf{r}_2(t_2)$ refers to any second handset, perhaps representing any one of a large number. It is therefore possible to use, as a temporary measure, a first handset at a known location as the LMU, offering the possibility of establishing an EOTD service very quickly in a new area.

We can also use this method even in an area already covered by an LMU. Having used a normal EOTD method to find the position of a handset, it (the handset) can then be tracked without further reference to the LMU. The calculation of the handset's position could be made at the MLC, at another location, or in the handset itself, depending on the application.

Another interesting application is to a system of many handsets in an area in which none of their positions is known. Provided that any pair sufficiently far apart can measure the same five BTSs, their positions can be determined using five equations like the three in (8). Otherwise, provided that separated pairs can measure at least three or four common BTSs, calculations based on many such measurements by pairs over a short period may be sufficient to determine the positions of all of them. Consider, for example, a set of three handsets, H_1, H_2, and H_3. The relative positions of H_1 and H_2, H_2 and H_3, and H_3 and H_1, may be computed using three or four BTS measurements since the constraints imposed by the equations on the positions of the vertices of the triangle $H_1H_2H_3$ may make the solution unique.

In the above discussions, we have made the assumption that the BTSs are frequency-locked together, i.e. that their signals are all locked to the same primary time standard so that their relative transmission delays (RTD) remain constant with respect to each other. It is possible to apply the invention to a network in which the BTSs signals are free-running with respect to each other, i.e. one in which there is no synchronisation of any sort between the transmissions. In this case, at least two handsets are required which can receive the signals from the same five geometrically-dispersed BTSs at substantially the same time as each other. Equations (11) then become

$$\Delta t_a = (|\mathbf{r}_1(t_1) - \mathbf{a}| - |\mathbf{r}_2(t_1) - \mathbf{a}|)/\upsilon + \varepsilon,$$

$$\Delta t_b = (|\mathbf{r}_1(t_1) - \mathbf{b}| - |\mathbf{r}_2(t_1) - \mathbf{b}|)/\upsilon + \varepsilon,$$

$$\Delta t_c = (|\mathbf{r}_1(t_1) - \mathbf{c}| - |\mathbf{r}_2(t_1) - \mathbf{c}|)/\upsilon + \varepsilon,$$

$$\Delta t_d = (|\mathbf{r}_1(t_1) - \mathbf{d}| - |\mathbf{r}_2(t_1) - \mathbf{d}|)/\upsilon + \varepsilon,$$

$$\Delta t_e = (|\mathbf{r}_1(t_1) - \mathbf{e}| - |\mathbf{r}_2(t_1) - \mathbf{e}|)/\upsilon + \varepsilon, \qquad \mathbf{(12)}$$

where **a**, **b**, **c**, **d**, and **e** are the vector positions of the five BTSs, $\mathbf{r}_1(t_1)$ is the vector position of the first handset and $\mathbf{r}_2(t_1)$ is the position of the second handset, both sets of measurements being made at the same time t_1. This moment could be signalled, for example, by a particular element of the transmissions such as a particular frame number or a special signal. In equations (12), the RTDs cancel out and do not appear provided that the measurements are made by the two handsets sufficiently close together in time that the drifts in the RTDs are small enough to ignore. The five measurements in equations (12) are sufficient to locate the two handsets. Note that no LMU or equivalent is required in this case.

An extension to this invention is to set up one or more VLMUs in a GSM or other transmission network which has no real LMUs at all. Timing measurements by handsets like those described above, especially in relation to equations (5) to (12), can be processed to provide a map of the BTS relative transmission delays, which may be

kept in the VLMUs and used in subsequent standard CURSOR or other EOTD position calculations. One might also imagine a system in which a sparse coverage of real LMUs is augmented in one or more VLMUs by handset measurements to provide the same level of service as from a full network of real LMUs.

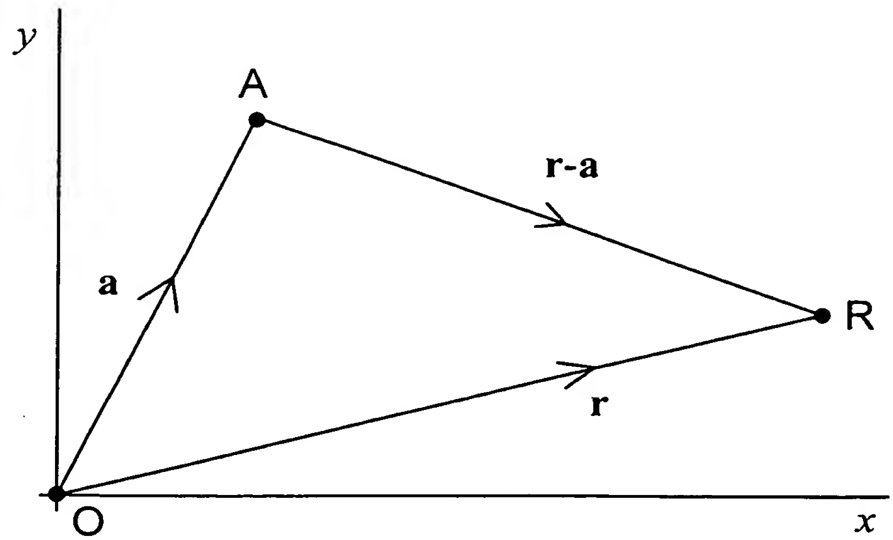

Figure 1

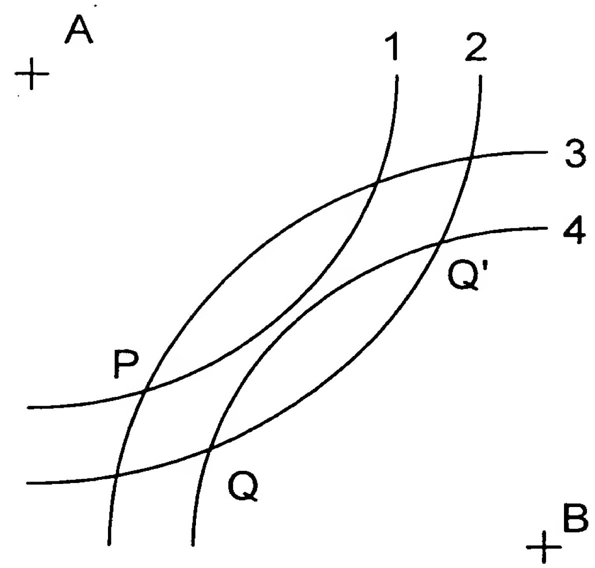

Figure 2

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